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PROPOSED NEAR FIELD SONAR TEST FACILITY NAVAL AIR REWORK FACILITY, NAVAL AIR STATION, NORTH ISLAND, SAN DIEGO

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Naval Research Laboratory
Washington, D. C.

April 1975

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NRL Memorandum Report 3016

Proposed Near Field Sonar Test Facility
Naval Air Rework Facility
Naval Air Station, North Island, San Diego

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Transducer Branch
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March 1975

NAVAL RESEARCH LABORATORY
Washington, D.C.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3016	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PROPOSED NEAR FIELD SONAR TEST FACILITY NAVAL AIR REWORK FACILITY, NAVAL AIR STATION, NORTH ISLAND, SAN DIEGO		5. TYPE OF REPORT & PERIOD COVERED A final report on one phase of a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) W. James Trott and A. L. Van Buren		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem S02-20 Project WR-4-0083; 17x4912.1953
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Rework Facility, Naval Air Station North Island, San Diego, CA 92135		12. REPORT DATE April 1975
		13. NUMBER OF PAGES 37
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustics
Sonar
Transducer calibration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A sonar calibration facility is designed for helicopter dipped sonar test and evaluation. Special requirements were, minimize space requirement, minimize ambient noise for low signal hydrophone calibration, treat water to increase cavitation threshold for source calibration. The nearfield calibration array technique provides an accurate, efficient calibration facility that can economically meet these special requirements.

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S/N 0102-014-6601

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CONTENTS

PROPOSED NEAR FIELD SONAR TEST FACILITY
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NAVAL AIR STATION, NORTH ISLAND, SAN DIEGO

INTRODUCTION

The Naval Air Rework Facility is charged with maintenance and overhaul of helicopter sonar currently designated AQS-10, AQS-13 and AQS-13B. A vital part of this program is the acoustic evaluation of the source and hydrophone array performance. The current work load is approximately 6 sources and 6 hydrophone arrays per month. Calibration services are obtained at Transdec, the general purpose, research calibration test facility of the Naval Undersea Center. The Naval Air Rework Facility should have a convenient in-house capability that is always set up for their test requirements and easily accessible for component adjustment or replacement when failure is indicated. There are three special requirements that can't be met with a facility such as Transdec. Test requirements have been modified with some question of reliability. 1) The standard test depth requires a reduction of the input power from 10 kW specified maximum to 5 kW to avoid cavitation and the attendant damage to the source that could occur. Water treatment can be used in a smaller test facility to raise the cavitation threshold by a factor of 10 or more. 2) The high sensitivity and vertical directivity specification of the hydrophone array require a very low ambient noise level in the test facility. Reference 1 reports the approximate ambient noise level in Navy facilities for underwater acoustic transducer calibration. The ambient noise level for Transdec, a ground supported tank, is not given but facilities of similar size show a noise level between Sea State 0 and 4. A facility designed to meet the AQS-10/13 hydrophone calibration requirement can be supported to minimize acoustic coupling to the ground, reduce transmission of machinery and road traffic noise and insure an ambient noise level below Sea State zero. 3) The third item is relative bearing between the flux gate compass and the hydrophone array. The test procedure calls for acoustic alignment of the initial zero setting for stiffness ratio measurements. The flux gate compass headings are related to an index pin. An acoustic calibration facility, not for general research, but designed and used only for helicopter sonar could be periodically surveyed and optically aligned for acoustic measurements relative to the same index pin used as a reference for compass alignment. There is too much chance of error in the present test procedure.

Note: Manuscript submitted February 14, 1975.

The design criteria for this type of test facility are: 1) measurements with sufficient accuracy must be obtained to show that the sonar meets all performance specifications, 2) diagnostic tests with sufficient accuracy must be obtained to indicate the nature of failure when performance specifications are not met, 3) the time required to make these measurements and the advantages of on-site accessibility must be balanced against the cost of the test facility and 4) the facility must be capable of handling future anticipated test requirements without extensive modifications. This report will show that a nearfield calibration facility can be built to satisfy the design criteria.

CALIBRATION PROCEDURES

In conventional measurements of underwater sound transducers [2] the sound pressure level emitted by a source is measured in the spherical wave region or far field. This region of spherical wave divergence, as would be obtained from an equivalent point source, is approximated only beyond a minimum distance, d, from the source to the measuring hydrophone,

$$d_m > \pi a^2/\lambda \text{ and } d_m > a$$

d_m = distance,

a = the largest radius or half length of a source depending on whether it is an area or line type source,

λ = the wavelength of the sound.

The source and hydrophone arrays of the AQS-10 and 13 are more like line arrays since the vertical height is the larger dimension. The reciprocal condition for the hydrophone array is the establishment of a plane-wave over the volume of the array. Thus

$$d_m > 11.7 \text{ feet}$$

For directivity measurement the equivalent plane wave must exist over the volume of the array when the direction of sound propagation is along the array staves. This requires a test distance ten times the length of the array or 27.3 feet. Since the staves are shaded, greatest sensitivity is in the center, this requirement can be relaxed to some extent. Assuming that 2 d_m is sufficient for directivity measurements the test distance should be greater than 23.4 feet.

A transducer calibration is generally performed in a water-filled tank or pond that imposes a limit on the test distance. The pulsed sound technique separates the desired, direct acoustic path, signal

from the undesired signals in the time domain. The desired signal is delayed by the test distance, d, divided by the speed of sound. The desired, acoustically reflected signals from the boundaries of the tank must be delayed sufficiently for steady-state conditions of the transducer being measured. This interference-free region must exceed the path length equal to Q wavelengths, where Q is the sharpness of resonance of the transducer, plus twice the active length of the transducer in the direction of propagation. This latter restriction is a function of orientation in directivity measurements. The dimensions of a tank can be related to the measurement test distance, d, and the required interference-free region, Δd.

$$\text{Tank length, } L > d + \Delta d$$

$$\text{Tank width and depth, } W > (L^2 - d^2)^{1/2}.$$

Thus, by these criteria, a tank for far field measurements of the source or the hydrophone array should be

$$L > 30 \text{ feet for 1 msec pulse}$$

$$W > 17 \text{ feet}$$

The most economical tank is a circular, wood stave tank of diameter 30 feet and depth 17 feet. The diameter must be increased by 5 feet for a 2 msec pulse etc. The test depth would be half of the water depth or 8 1/2 feet. This assumes that the water would be treated to raise the cavitation threshold.

As stated earlier, the test distance requirement for far-field measurement of a finite receiver in the field of a point source is the same as for a point receiver and a finite source. That is, the system consisting of two transducers connected by the acoustic path is a reversible system independent of the direction of transmission. Stating the test conditions in another way, the wave front must be substantially plane in the region of a finite receiving transducer. By a particular control of the source strength of the elements in a multi-element planar array transducer it is possible to produce a plane-wave sound field of constant amplitude over a finite region close to this array, in its near field. Within this sound field a finite receiver can be measured in the same way it would be measured by a point source at the minimum far-field test distance, d_m. Furthermore, in this non-diverging sound field the test distance need not be measured. If the near-field measuring array is acoustically transparent its close proximity will not affect the measurement. This system, array and finite receiver is also a reversible system. That is, the array, receiving, will correctly measure a finite transducer source within its near sound field. This is the basis of one successful near-field measuring technique [3].

Theory and data on the first near-field, plane array were presented in an invited paper at the November 1962 meeting of the Acoustical Society of America. A sonar transducer was calibrated by near-field and far-field techniques at Boston Naval Shipyard in January 1964. Agreement was good, well within the accuracy of far-field measurement of sensitivity, response and directivity. A second, larger array was built and measurements were reported at various Navy symposia and committee meetings. In 1964 a Naval Research Laboratory Memorandum Report showed the design computations for a proposed large near-field plane array. This array, which measured 33 feet square and contained 2,500 elements, met all expectations when it was evaluated at the NRL Lake Seneca (New York) facility in 1968. The Underwater Sound Reference Division of NRL (Orlando, Florida) has one plane array 10 feet square [4] and an array for the anechoic pressure tank facility [5].

A plane array of approximately 7 feet diameter will produce the required volume for nearfield measurement of the projector or hydrophone array. The test distance d_m is reduced to less than 3 feet. Since the measuring and measured transducers are no longer small in relation to the dimensions of the tank the minimum tank dimensions must be corrected for proximity of the extremities of the transducers to the tank walls. The minimum tank dimensions are 10 feet diameter by 8 feet deep for a 1 msec pulse and 15 feet diameter by 13 feet deep for a 2 ms. pulse as shown in Fig. 1. Fig. 2 shows minimum tank dimensions for the range of 1 to 5 msec pulse.

In each of these proposed calibration tanks the transducer depth is half the water depth. These shallow depths are convenient for handling and for accurately positioning the transducers but require some water treatment to prevent cavitation at the maximum projector source level. For the required farfield calibration tank and a test depth of 8 1/2 feet an approximate value of the cavitation threshold [6]

$$I_c = 0.15(1 + \frac{8.5}{33})^2 \text{ watts/cm}^2 = .25 \text{ watts/cm}^2$$

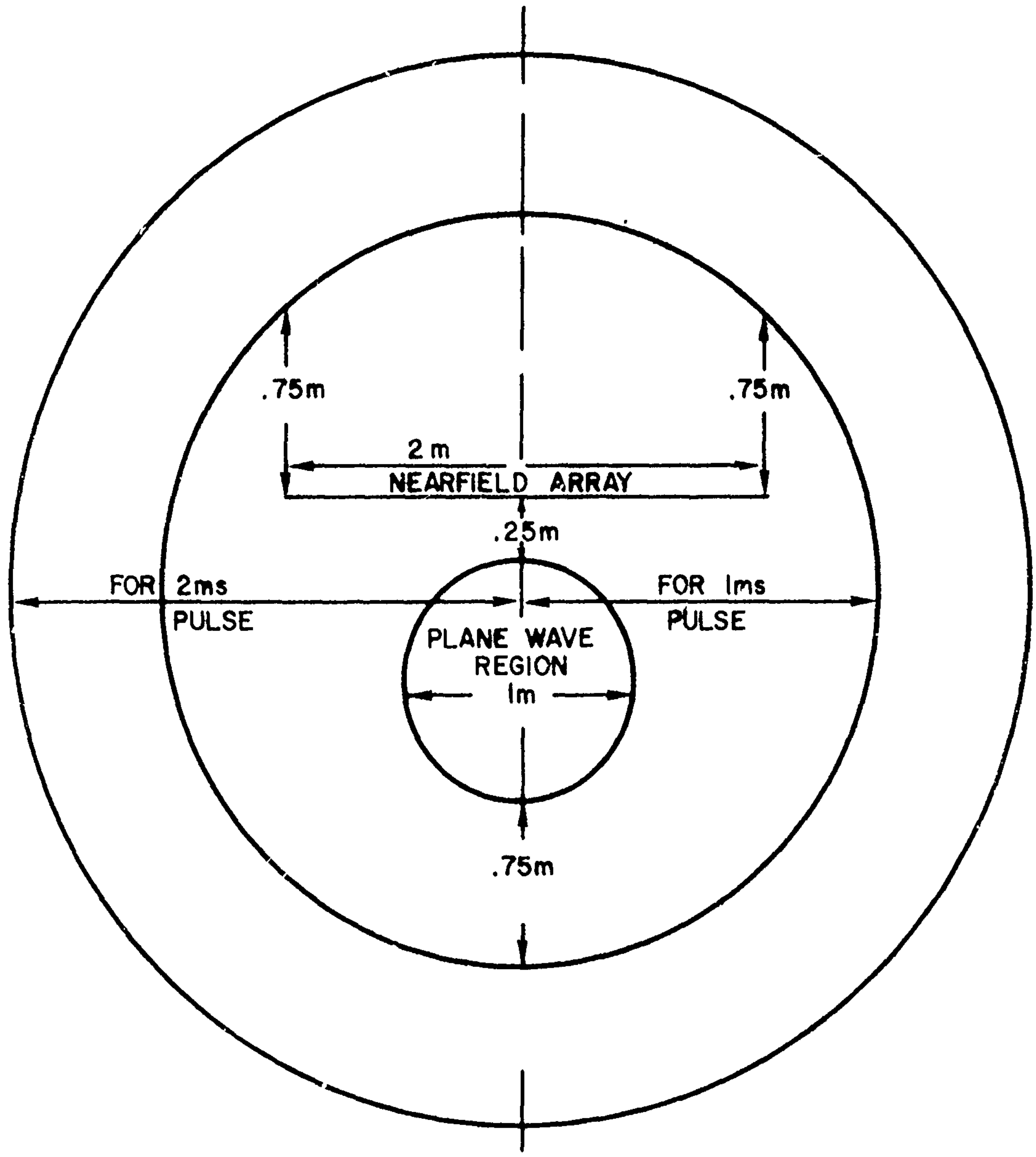
and for the nearfield calibration tanks the cavitation threshold would be less.

The maximum projector source level

$$SL = 111 \text{ dB re } 1\ \mu\text{bar at } 1 \text{ yd} = 110.2 \text{ dB re } 1\ \mu\text{bar at } 1\text{m}$$

directivity index

$$DI > 7.5 \text{ dB}$$



DEPTH OF WATER

(8.2 ft) 2.5m FOR 1 msec PULSE

(13.1 ft) 4m FOR 2 msec PULSE

Fig. 1 — Tank geometry for nearfield calibration with 1 and 2 msec pulse

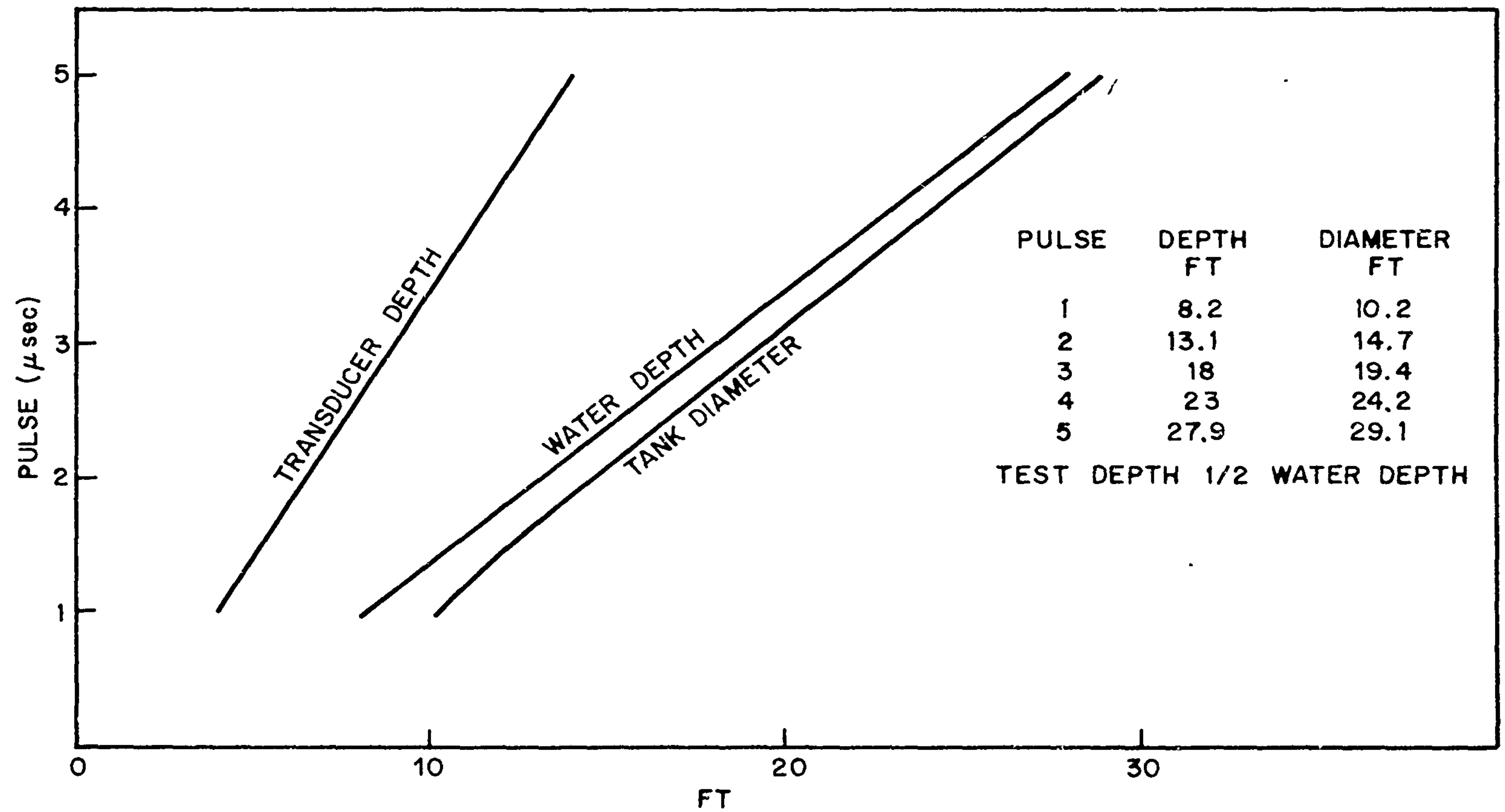


Fig. 2 — Minimum tank dimensions versus pulse duration

thus

Total radiated power

$$L_w = SL - DI - 70.9 \text{ dB re 1 watt}$$

$$110.2 - 7.5 - 70.9 = 31.8 \text{ dB re 1 watt or 1514 watts}$$

Taking the dimensions of the source

23.1 inches long 58.7 cm

7.8 inches diameter 19.8 cm

Area = 3654 cm^2

or the sound intensity is

$$I = .4 \text{ watts/cm}^2$$

Obviously at full power the projector is subject to cavitation and could be damaged if measured at maximum power at these calibration depths without some form of water treatment to strengthen the water and increase its cavitation threshold. To operate this transducer at full power in untreated water the test depth must exceed 20 feet or the calibration tank must be pressurized greater than 10 psi above atmospheric pressure.

WATER TREATMENT TO INCREASE CAVITATION THRESHOLD

The cavitation threshold has been increased by a factor of 10 by deoxygenation and by chemically treating the water [7]. Deoxygenation to .4 ppm (2% of saturation) was accomplished by placing steel wool or steel punchings in water-filled natural rubber balloons that were placed in the calibration tank. Oxidization of the steel occurred due to the high permeability of the rubber to oxygen. The rust was retained in the balloon so the tank water remained clean. In the oxidizing process some hydrogen gas is formed. This was dissolved in the water and added strength to the water. When additional hydrogen was formed through battery action in the water the cavitation threshold increased by a factor of 23 over the untreated fresh water threshold. Thus deaeration to 0.4 ppm (2% of saturation will raise the cavitation threshold to 0.7 w/cm^2 or sufficient for full power (0.4 w/cm^2) calibration in the minimum size tank for nearfield calibration, Fig. 3. Deaeration for arresting corrosion and bacterial growth in water feed systems is standard procedure using a vacuum tower and liquid ring vacuum pump [8].

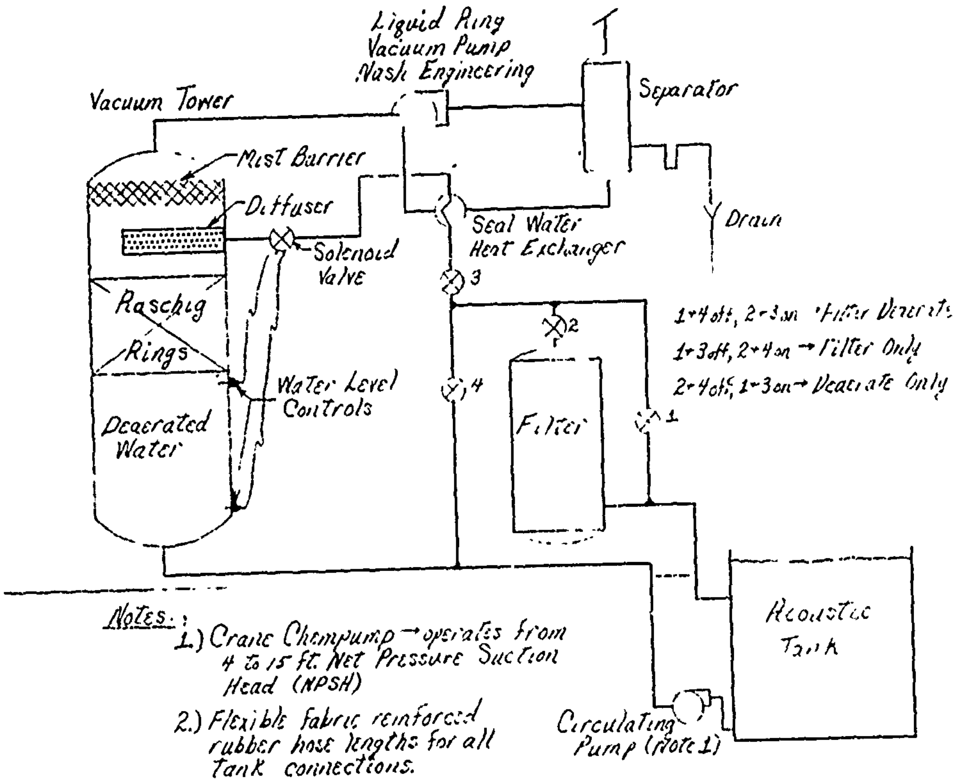


Fig. 3 — Water treatment system

The cavitation threshold can also be increased by a factor of 10 by the addition of polysaccharides, a chemical that marine organisms exude into the sea [7]. This was obtained by distillation from algae culture and the crystal residue dissolved in the calibration tank to a level of 7 grams of crystal per cubic foot of water. If this procedure were used with water purification (chlorination) the chemical compatibility would have to be determined. Dr. J.W. Hoyt of the Naval Undersea Research and Development Laboratory at Pasedena, California, has knowledge of this material.

MEASUREMENT TANK SUPPORT TO REDUCE AMBIENT NOISE

The general test specifications for calibration of the sonar hydrophone call for a sound pressure level at the hydrophone

$$SPL = 15 \pm 2\text{dB re } 1\ \mu\text{bar}$$

$$115 \pm 2\text{dB re } 1\ \mu\text{Pa}$$

The hydrophone sensitivity

$$M_H = -15 \pm 2\text{dB re } 1\ \text{V}/\mu\text{bar}$$

$$-115 \pm 2\text{dB re } 1\ \text{V}/\mu\text{Pa}$$

The signal level $SPL + M_H = 0\text{dB re } 1$ Volt

In the measurement of the vertical beam pattern the direction toward the ocean surface must be -40dB or less referred to the beam axis sensitivity. Thus the noise level (NL) measured by the sonar hydrophone must be less than -60dB re 1 Volt. In this measurement

$$NL - DI + M_H = -60\text{dB re } 1 \text{ Volt}$$

or

$$NL = DI - M_H - 60$$

The directivity index DI = 18dB

$$NL = 18 + 15 - 60 = -27\text{dB re } 1\ \mu\text{bar}$$

$$73\text{dB re } 1\ \mu\text{Pa}$$

In pulsed sound measurements the bandwidth of the receiving system should be 2 to 20 times the reciprocal of the pulse duration. This suggests a bandwidth of 10^4 Hz for the pulse duration of 1 to 2 msec. Therefore the spectral noise level SNL

$$\text{SNL} = -27 - 10 \log(10^4) = -67\text{dB re } 1\ \mu\text{bar}$$

$$33\text{dB re } 1\ \mu\text{Pa}$$

This is approximately Sea State 1 in the region of 10kHz. The ambient spectral noise level in the room must be -6dB due to the approximate pressure doubling in transfer from air to the water [9, 10]. Thus the air spectral noise level must be less than

$$-73\text{dB re } 1\ \mu\text{bar}$$

$$27\text{dB re } 1\ \mu\text{Pa}$$

or

$$1\text{dB re } 20\ \mu\text{Pa}$$

Reference 1 shows ambient noise levels in Navy owned facilities ranging from equivalent 0 to 6 Sea State. It would seem prudent to design this proposed facility for minimum coupling to ground noise and vibration and plan some noise isolation for the room. Room acoustics can be treated after installation. Tank support must be incorporated into the design plan. The NRL Acoustic Calibration Tanks are mounted on 4 inch thick blocks of cork. With all pumps and fans in the room shut off the equivalent noise pressure level under water in these tanks is below Sea State zero. The effectiveness of its transmission loss is not known and the effects of time and possible water content for the planned facility environment are unknown variables. Spring mounting of the tank would be useful at very low frequencies but, in the range of 10kHz, conduction along the spring wire from ground to tank could be appreciable. The use of air bags to support the tank is known to yield more than 99.9% isolation. One type produced by Firestone Industrial Products Co. would support the tank and isolate it from ground noise and vibration. Air pressure of 60 psi is required. The double convolution style air mount could be contained in a pipe to maintain lateral stability and this would not effect the isolation nor would it cause wear for the small vibration amplitudes in this application. About 12 units would be required in positions around the perimeter of the tank near the bottom. For the tank dimensions in Fig. 2

1 msec pulse, 5,000 gallons Airmount #22

2 msec pulse, 17,000 gallons Airmount #203

3 msec pulse, 40,000 gallons Airmount #211

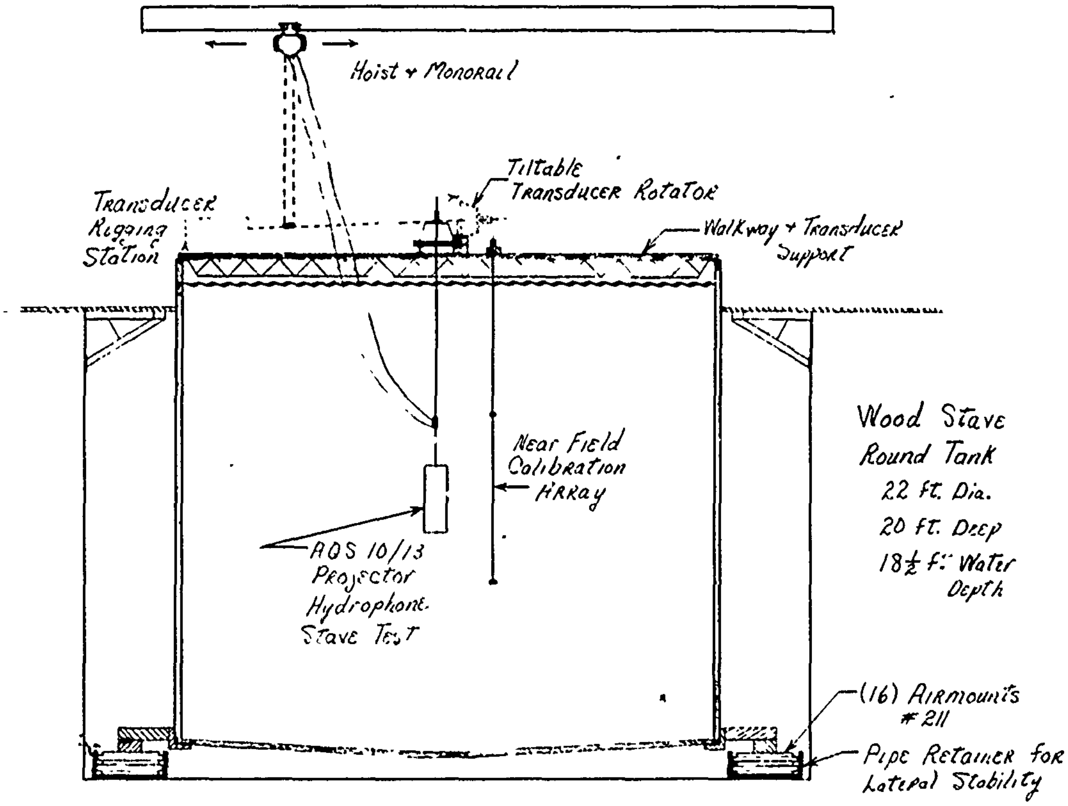


Fig. 4 — Proposed calibration tank

The manufacturers have expressed the opinion that leveling valves would not be necessary. Groups of the air springs could be controlled by self-relieving pressure regulators set to the required design height. If constant height is required the Bendix-Westinghouse LV-2 leveling valves could be used.

Bendix-Westinghouse Automotive Air Brake Co.
901 Cleveland, Elyria, Ohio

Other manufacturers

Delco Products Division of GMC
Dayton, Ohio

Power Control Division
Midland Ross Corp.
Owosso, Michigan

Wagner Electric Corp.
St. Louis, Missouri

The Airmounts are priced in the range of $300.

TRANSDUCER FIXTURES AND HANDLING

In the conventional far-field calibration technique the test distance between the projector and hydrophone depends upon the size of the transducers and the test sound frequency. Generally the calibration is performed at several test distances and the data corrected for spherical wave divergence to test the validity of the data. For these reasons a far-field calibration facility must employ rolling carriages on tracks to support the transducers. Rolling carriages can cause errors in the orientation of the transducers and the measurement of the test distances between the projector and hydrophone.

In the near-field calibration array technique the hydrophone is positioned in the plane-wave, near-field of the array. The test distance need not be measured and the test distance need not be varied. If the test distance is varied it is done only to periodically check the accuracy of the plane-wave region. The system of array and hydrophone is a reciprocal system so the measured transducer can be a source and the NFCA used to receive.

It is proposed that this facility be constructed with fixed positions of the measured transducer and the NFCA to reduce errors in orientation. The NFCA can be optically aligned with a telescope or laser. The measured transducer can be attached to a rotator that is mechanically coupled to the bridge structure in the center of the plane-wave volume of the NFCA that is also attached to the rotator support. The AQS-10/13 projector is calibrated with its normally

vertical axis in the horizontal plane. As a periodic check of the plane-wave region of the NFCA, the projector could be positioned above and below the normal calibration depth and the center of the projector could be offset from the axis of the rotator shaft. The projector would remain within the calibrating region for positions 12 inches (30 cm) above and below the normal calibration depth and 6 inches (15 cm) offset from the rotation axis. The measured vertical directivity patterns for all positions and all three operating frequencies should agree.

Figure 4 shows the tank for calibration using up to a 3 msec pulse duration. Since the measured transducer can be attached to a rotator mechanically coupled to the bridge structure at one position, the rotator can be hinged and tiltable so that all transducer rigging can be done on the bridge at the side of the tank. In the figure the ASQ-10/13 hydrophone array is shown rigged for azimuth sum and difference pattern measurements. It is believed that the standard hydrophone mount now used is mechanically strong enough for this method of handling. In the measurement of hydrophone vertical patterns the rigging may be too light for this method of handling. The U frame for vertical pattern measurements must be acoustically transparent for the measurement accuracy specified in the vertical axis direction. It may be necessary to hinge the U frame at the rotator shaft so the hydrophone and U frame remain vertical when the rotator is tilted up for rigging. The rotator shaft is hollow so a rod pin could be used to lock this hinge during calibration. Ceiling clearance requirements are less if a tiltable rotator is used. A monorail hoist is shown with a track parallel with the bridge for installation of the equipment and for raising the tiltable rotator.

An underwater rotator, not shown, would reduce the rigging and handling time considerably. An underwater rotator like the Scientific-Atlanta Model 1131-2-0 could support the projector, the hydrophone array or a stave in a position that places the normally vertical axis of the ASQ-10/13 in the horizontal plane. This rotator would be used in the measurement of azimuth receiving patterns, stiffness ratio and for positioning on the beam axis for measurement of beam sensitivity. The bridge-mounted, tiltable rotator would be used for measurement of projector and hydrophone vertical beam pattern characteristics. Projector and hydrophone array would be rigged in the acoustic test position only once each for all measurements instead of being repositioned between azimuth and vertical beam measurements. The problem is that, although this underwater rotator would be attached where the projector and hydrophone are normally joined, its 15 inch diameter face would be a strong reflector. The specified -40 dB re main beam level for hydrophone array sensitivity looking up along the vertical axis is normally measured in the presence of an acoustically transparent yoke support structure. The axis of the bridge rotator must be within 6 inches (15 cm) of the center of the measured transducer to keep the transducer within the calibration region of the NFCA. To avoid the interfering reflection from the submerged rotator it would have to be positioned

off axis by 2 1/2 feet for a 1 msec pulse, 5 feet for a 2 msec pulse or 7 1/2 feet for a 3 msec pulse. An acceptable 250° of rotation of the bridge mounted rotator would be possible. In raising the transducer to the rigging station the submersible rotator would be positioned directly below the transducer. This would require some rotation of the bridge rotator during the hoisting operation. If the 7 1/2 feet offset is specified then the Model 1131-3-0 with a 1000 lb. ft. bending moment limit would be required. If the bridge for transducer mounting is built over the tank with support from the floor then rubber-in-shear, vibration isolation mounts will be required between the bridge and the floor to remove this ground-conducted noise path. All pipe connections between the tank and the water treatment equipment should be isolated with a length of fabric-reinforced hose.

DESIGN OF THE HEXAGONAL PLANAR NEARFIELD CALIBRATION ARRAY.

The proposed nearfield calibration array (NFCA) is a hexagonal planar array, as shown in Fig. 5. The parameters used to define a hexagonal NFCA are the tier number n, obtained by counting from the center element of the array along one of the six major diagonals to the edge of the array, and the spacing d between elements. For the illustrated array, n is equal to 13. The total number of elements in a hexagonal array is given by $N = 1 + 3n(n - 1)$. The length of a major diagonal is given by $L = 2(n - 1)d$.

The elements in a hexagonal NFCA are shaded so that the array, when each element is driven with unit input current, produces a nearly uniform plane wave in the direction $\hat{e}$ of the outward normal to the array over a volume V in its nearfield and over a given frequency range Ω [11]. By reciprocity, the response of the NFCA to an unknown transducer T placed in V and driven at any frequency in Ω is proportional to the farfield pressure distribution of T in the direction $-\hat{e}$.

For the present study the volume V must be large enough to contain a cylindrical hydrophone of length 32.8" and diameter 16.3" as it is being rotated to determine both the horizontal and vertical farfield pressure distributions. The maximum extent of this hydrophone is equal to

$\sqrt{(32.8")^2 + (16.3")^2} = 36.63" = 0.93m$. Therefore, a suitable volume V is a sphere of radius 0.5m. The desired test frequencies are 9.25 kHz, 10.0 kHz, and 10.75 kHz so Ω is taken to be the frequency range 9 - 11 kHz. The spacing d is taken to be 0.095m. The ratio d/λ is then equal to 0.59, 0.63, and 0.68 for 9.25 kHz, 10.0 kHz, and 10.75 kHz, respectively. (The sound speed is assumed to be 1500 m/sec). A Cartesian coordinate system is established with its origin (x,y,z) = (0,0,0) at the center of the array and with its z axis normal to the array. The center of the volume V is located at (0,0,0.75m).

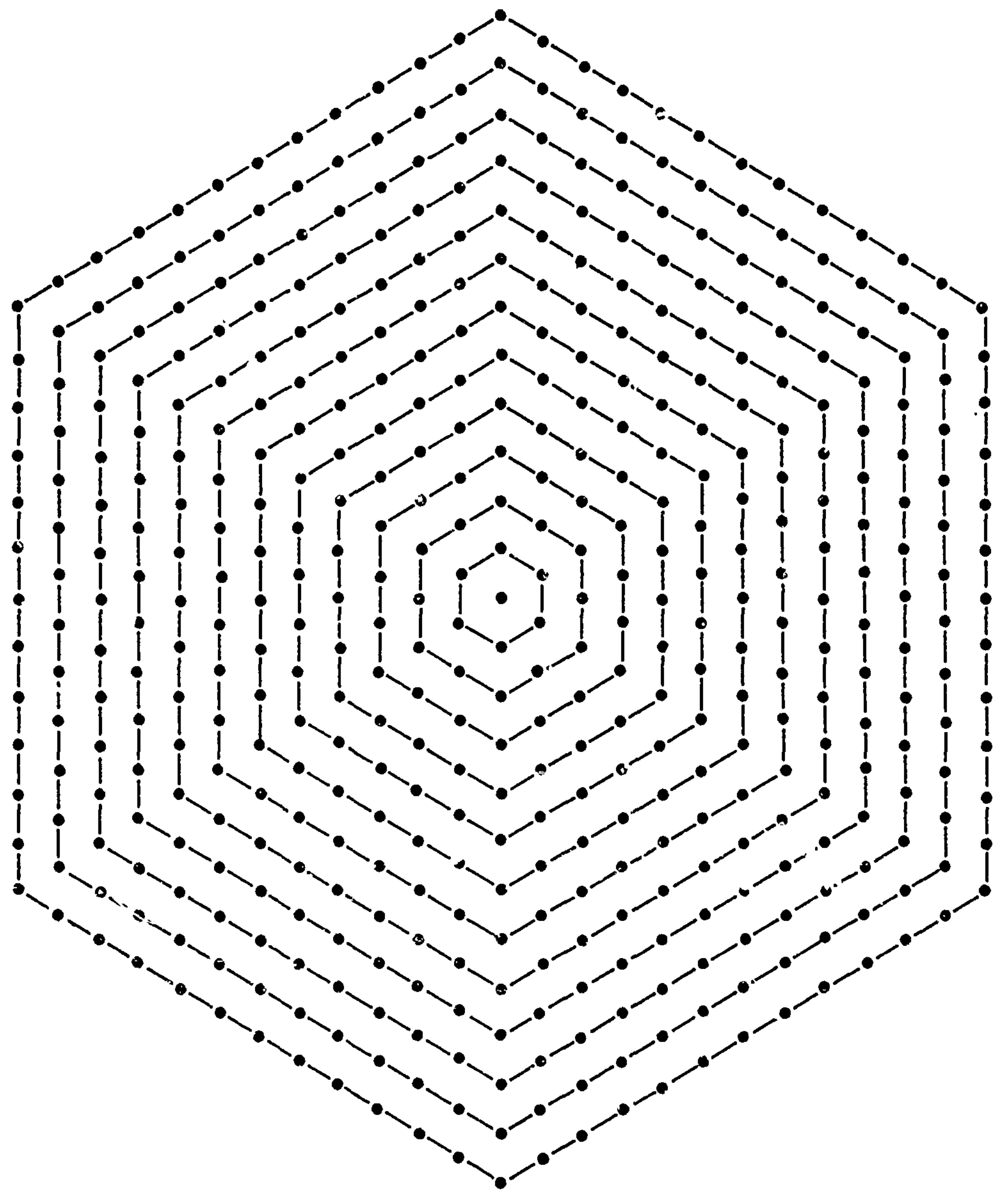


Fig. 5 -- Element configuration for hexagonal nearfield calibration array

We now consider possible sizes for the NFCA. The number of tiers n, total number of elements N, and the widths L for several alternative arrays are listed in Table I.

TABLE I. ALTERNATIVE HEXAGONAL NFCA'S

n	N	L
9	217	1.52m
10	271	1.71m
11	331	1.90m
12	397	2.09m

Obviously, the ability of the NFCA to produce a nearly uniform plane wave over a given volume and frequency range depends on the size of the array. Thus the 12 tier array can be shaded to produce a wave field that, in theory, more closely approximates a plane wave than that produced by any of the smaller arrays. However, in practice, nonuniformities in element construction and irregularities in element location in the array result in a greater deviation from plane-wave conditions than would be predicted theoretically assuming ideal conditions.

Either real (amplitude only) or complex (containing both amplitude and phase) shading coefficients can be obtained for a given array size. There are n coefficients W_n, one for each tier of elements, i.e., the center element is shaded with W_1, the six surrounding elements are shaded with W_2, etc. The coefficients have the dimensions of area; the coefficient W_1 is nearly equal to the effective area of one element in the array, i.e., $d^2\sqrt{3}/2$. It is convenient to normalize the set of coefficients so that W_1 is equal to unity.

The required shading is implemented experimentally by connecting the elements in each tier in parallel, shading each tier externally by W_n, and obtaining the response of the array by connecting in parallel all the shaded tier responses. If real shading coefficients are used, the required amplitude shading can be obtained at all frequencies from 9 - 11 kHz by a single passive network (e.g., voltage divider) for each tier. This is not the case for complex shading coefficients. The complex coefficients obtained by the methods described in Reference 1 have a phase angle that is constant over the frequency range Ω. If one uses, for example, a time delay to produce the phase shading, different time delays are required for different frequencies. Thus one must use a separate passive network for each desired frequency. In the present case this would require three networks for each tier (except the first). Offsetting this disadvantage is the significantly better plane-wave uniformity produced by complex shading as compared with

real shading for the same size array. A compromise solution when the bandwidth of Ω is reasonably small is to use a single network for each tier that contains a time delay appropriate to the center of the band. In the present case this corresponds to using the time delay necessary to give the correct phase shift at 10.0 kHz and allowing small phase errors to result when the shading network is used at 9.25 kHz and 10.75 kHz. The resultant plane-wave uniformity will probably be better than that obtained using real coefficients.

Both real and complex shading coefficients were obtained for arrays of 9, 10, 11, and 12 tiers. All of the sets of coefficients except for the real set for 9 tiers, together with the unnormalized value of W_1, are given in Tables II - VIII.

The plane wave uniformity produced using these coefficients was tested at a large number of points throughout the volume V and at the three frequencies 9.25 kHz, 10.0 kHz, and 10.75 kHz. The ranges of both the pressure amplitude and the deviation from the plane-wave phase are given in Table IX. The average plane-wave nonuniformity is considerably less than the extrema presented here. There are also entries in Table IX for the case where the required phase shifts are produced by time delays that are appropriate for 10.0 kHz. Here the resulting phase shifts, including that of the normalization, for 9.25 kHz and 10.75 kHz are the correct phase shifts multiplied by 0.925 and 1.075, respectively. This produces a systematic nonuniformity in the plane-wave field. Consequently, the average nonuniformity in this case is closer to the extrema given in Table IX. The shading coefficients are ranked according to the plane-wave uniformity they produce, as shown in Table X.

Therefore, if ultimate theoretical plane-wave uniformity is desired, the choice is C12 with 3 sets of time delay circuits, one for each frequency. However, the set C10 produces a uniformity that is quite adequate. In fact, in practice the results obtained using C12 would probably not be significantly better than with C10, due to experimental nonuniformities. The set R12 is a good choice if one does not wish to use complex coefficients, although the array contains 116 more elements than with C10. The set C9 represents a decrease of 180 elements from either C12 or R12, but the plane-wave nonuniformity is beginning to get larger than desired.

In conclusion, the choice seems to be as follows: if one is willing to build 3 sets of time delays, use C10; if one is only willing to build 1 set of time delays, use C12; or if one wishes real shading, use R12.

TABLE II. Normalized* Complex Shading Coefficients for a 12 Tier Hexagonal NFCA (called set C12)

Tier	Amplitude	Phase (°)
1	1.0000	0.0
2	0.8123	-4.4
3	0.8962	0.9
4	0.8916	-6.4
5	0.7613	-1.6
6	0.9130	8.9
7	1.1685	-1.6
8	1.1766	-22.9
9	0.9014	-46.9
10	0.5074	-70.3
11	0.1899	-92.0
12	0.0358	-111.0

*The normalization W_1 has amplitude 9.015×10^{-3} m^2 and phase 2.2°. The assumed time dependence is $\exp(i\omega t)$, so that a negative phase angle corresponds to a positive time lead.

TABLE III. Normalized* Real Shading Coefficients for a 12 Tier Hexagonal NFCA (called set R12)

Tier	Amplitude
1	1.0000
2	1.0060
3	1.0046
4	1.0036
5	1.0006
6	0.9925
7	0.9668
8	0.9043
9	0.7728
10	0.5523
11	0.2906
12	0.0824

*The normalization W_1 is equal to 7.771×10^{-3} m^2.

TABLE IV. Normalized* Complex Shading Coefficients for an 11 Tier Hexagonal NFCA (called set C11)

Tier	Amplitude	Phase (°)
1	1.0000	0.0
2	0.6569	11.8
3	0.8668	9.8
4	0.7249	-0.2
5	0.6604	18.8
6	0.9776	18.9
7	1.1345	-2.5
8	0.9617	-28.8
9	0.5899	-55.1
10	0.2399	-79.7
11	0.0494	-101.4

*The normalization W_1 has amplitude $1.017 \times 10^{-2} m^2$ and phase -8.3°.

TABLE V. Normalized* Real Shading Coefficients

for an 11 Tier Hexagonal NFCA (called set R11)

Tier	Amplitude
1	1.0000
2	1.0411
3	1.0294
4	1.0281
5	1.0204
6	0.9975
7	0.9453
8	0.8399
9	0.6371
10	0.3750
11	0.1285

*The normalization W_1 is equal to $7.553 \times 10^{-3} m^2$.

TABLE VI. Normalized* Complex Shading Coefficients

for a 10 Tier Hexagonal NFCA (called set C10)

Tier	Amplitude	Phase (°)
1	1.0000	0.0
2	0.7061	40.7
3	0.9355	20.9
4	0.6040	18.2
5	0.7989	46.4
6	1.1950	28.9
7	1.1854	-0.5
8	0.8182	-31.6
9	0.3691	-61.9
10	0.0838	-90.2

*The normalization W_1 has amplitude $1.000 \times 10^{-2} m^2$ and phase -26.0°.

TABLE VII. Normalized* Real Shading Coefficients for a 10 Tier Hexagonal NFCA (called set R10)

Tier	Amplitude
1	1.0000
2	0.9890
3	0.9933
4	0.9851
5	0.9699
6	0.9371
7	0.8578
8	0.6769
9	0.4299
10	0.1675

*The normalization W_1 is equal to $7.857 \times 10^{-3} m^2$.

TABLE VIII. Normalized* Complex Shading Coefficients for a 9 Tier Hexagonal NFCA (called set C9)

Tier	Amplitude	Phase(°)
1	1.0000	0.0
2	0.9327	99.0
3	0.9606	50.8
4	0.3748	80.4
5	1.0579	95.1
6	1.3759	59.9
7	1.0985	22.2
8	0.5543	-14.8
9	0.1410	-50.1

*The normalization W_1 has amplitude $1.043 \times 10^{-2} m^2$ and phase -70.4°.

TABLE IX. Plane-Wave Uniformity Obtained Using Selected Hexagonal NFCA's

Set	Frequency (kHz)	Delay Frequency (kHz)	Pressure Amplitude Minimum	Pressure Amplitude Maximum	Phase Deviation (°) Negative	Phase Deviation (°) Positive
C12	9.25	9.25	0.994	1.004	-0.3	0.2
	10.0	10.0	0.996	1.005	-0.3	0.2
	10.75	10.75	0.997	1.006	-0.3	0.2
C12	9.25	10.0	0.970	1.029	-1.1	1.8
	10.75	10.0	0.974	1.018	-1.6	1.2
R12	9.25		0.969	1.040	-1.2	4.5
	10.0		0.973	1.038	-0.6	4.1
	10.75		0.960	1.019	-0.4	3.3
C11	9.25	9.25	0.985	1.006	-0.9	0.4
	10.0	10.0	0.990	1.008	-0.9	0.2
	10.75	10.75	0.994	1.011	-0.8	0.4
C11	9.25	10.0	0.958	1.038	-2.2	2.1
	10.75	10.0	0.959	1.038	-2.2	2.4
R11	9.25		0.903	1.062	-1.4	8.2
	10.0		0.911	1.046	-1.5	6.5
	10.75		0.913	1.027	-1.3	5.7
C10	9.25	9.25	0.970	1.020	-3.0	0.8
	10.0	10.0	0.979	1.027	-2.8	1.2
	10.75	10.75	0.986	1.034	-2.5	1.9
C10	9.25	10.0	0.948	1.049	-1.6	2.8
	10.75	10.0	0.945	1.044	-3.3	1.8
R10	9.25		0.799	1.099	-1.9	13.5
	10.0		0.805	1.087	-1.7	13.2
	10.75		0.812	1.053	-1.7	11.8
C9	9.25	9.25	0.950	1.033	-4.8	1.5
	10.0	10.0	0.961	1.046	-4.6	1.1
	10.75	10.75	0.972	1.060	-4.4	2.0

TABLE X. Ranking of Hexagonal NFCA Shading Coefficients on the Basis of Theoretical Plane-Wave Uniformity

Rank	Set of Coefficients
1	C12
2	C11
3	C10
4	C12, with a single time delay
5	R12
6	C11, with a single time delay
7	C9
8	C10, with a single time delay
9	R11
10	R10

CALIBRATION MEASUREMENTS AND MEASURING SYSTEM

The near-field calibration array (NFCA) will be constructed of capped piezoceramic tubes 1/2" diam., 1/2" long, 1/8" wall or 1.27 cm diameter and length and .32 cm wall. The material will be Mil. Std. Type I, a hard lead zirconate-titanate ceramic. The free-field voltage sensitivity of the array is the element sensitivity or

$M_{NFCA} = -204$ dB re 1 V/μPa

-104 dB re 1 V/μbar

The plane-wave, near-field transmitting current response is derived from the plane-wave reciprocity parameter

$$S_{NFCA} = M_{NFCA} - 20 \log \left(\frac{2A}{\rho c}\right)$$

where ρc is the plane wave impedance, A is the effective area of the array. The area is the effective piston source area; $A = 2.3\ m^2$ for the 12 tier array. Expressed in SI units and r.m.s. values

$$S_{NFCA} = -84 + 110.3 = 26.3 \text{ dB re 1 Pa/amp}$$

$$= 146.3 \text{ dB re 1 μPa/amp}$$

$$= 46.3 \text{ dB re 1 μbar/amp}$$

With shading capacitors the impedance of the 12 tier array will be 51 ohms at 10 kHz.

To obtain the specified sound pressure level for measurement of the hydrophone array the source level SL_{NFCA}

$$SL_{NFCA} = 15 \pm 2 \text{ dB re 1 μbar}$$

$$SL_{NFCA} = S_{NFCA} + 20 \log I$$

or $20 \log I = 15 - 46.3 = -31.3$ dB re 1 amp

$$I = 27 \text{ ma}$$

To measure the projector at full power delivering a specified source level (SL_p) of 111 dB re 1 μbar at 1 yd. or 91 dB re 1 Pa at 1 yd.

$$SL_p = 20 \log (E_{NFCA}) - S_{NFCA} - 20 \log J_s$$

where $J_s = \frac{2d\lambda}{\rho c}$ the spherical wave reciprocity parameter, d is the reference distance 1 yd. or .91 m and λ is the wave length of the sound

$$20 \log (E_{NFCA}) = 91 + 26.3 - 134.8 = -17.5 \text{ dB re 1 V}$$

or E_{NFCA} = 0.13 Volts at 10 kHz driving the AQS 10/13 at full power of 10 kVA if it delivers a source level of 111 dB re 1 μbar at 1 yd.

These are design values. The NFCA will be calibrated in terms of its plane-wave near-field transmitting current response S_{NFCA} by driving it at a known current and measuring the sound pressure level with a standard hydrophone located at several positions in the plane-wave, near-field measurement region. This calibration should be repeated at 1 month intervals when the array is in use. A standard NRL-USRD type H56 hydrophone is suitable for this measurement since it has a very low equivalent noise pressure level, -10 dB re Sea State 0 to 10 kHz. With this measured S_{NFCA} the free-field voltage sensitivity of the unknown M_x is

$$M_x = 20 \log E_x - 20 \log p = 20 \log E_x - 20 \log (I_{NFCA}) - S_{NFCA}$$

The pressure unit in this equation can be μbars or μPa.

The source level of the unknown projector in SI units

$$SL_x = 20 \log (E_{NFCA}) - S_{NFCA} - 20 \log (J_s)$$

For the specified source level in dB re 1Pa at 1 yd. or 0.91 meters

$$20 \log (J_s) = 20 \log \left(\frac{2(.91)}{10^3 f}\right) = -134 \text{ dB at 9.25 kHz}$$

$$-134.8 \text{ dB at 10 kHz}$$

$$-135.4 \text{ dB at 10.75 kHz}$$

The S_{NFCA} will be approximately the design value derived above 26.3 dB re 1Pa/amp and the source level of the unknown

$$SL_x = 20 \log (E_{NFCA}) - 26.3 - 20 \log (J_s) \text{ dB re 1Pa at 1 yd}$$

$$+ 120 \text{ in dB re μPa at 1 yd}$$

$$+ 20 \text{ in dB re μbars at 1 yd}$$

In terms of dB re 1 μPa at 1 yd $SL_x = 20 \log (E_{NFCA}) + 227.7$ at 9.25kHz

$+ 228.5$ at 10 kHz

$+ 229.1$ at 10.75 kHz

In terms of dB re 1 μbar at 1 yd

$$SL_x = 20 \log (E_{NFCA}) + 127.7 \text{ at } 9.25 \text{ kHz}$$

$$+ 128.5 \text{ at } 10 \text{ kHz}$$

$$+ 129.1 \text{ at } 10.75 \text{ kHz}$$

To measure the transmitting current response of the AQS 10/13 projector the driving current must be measured. Then in terms of dB re 1 μPa per amp at 1 yd

$$S_x = 20 \log (E_{NFCA}) - 20 \log I + 227.7 \text{ at } 9.25 \text{ kHz}$$

$$+ 228.5 \text{ at } 10 \text{ kHz}$$

$$+ 229.1 \text{ at } 10.75 \text{ kHz}$$

and in terms of dB re 1 μbar per amp at 1 yd

$$S_x = 20 \log (E_{NFCA}) - 20 \log I_x + 127.7 \text{ at } 9.25 \text{ kHz}$$

$$+ 128.5 \text{ at } 10 \text{ kHz}$$

$$+ 129.1 \text{ at } 10.75 \text{ kHz}$$

Efficiency (η) is calculated from the transmitting current response (dB re 1 μbar per amp at 1 yd), the transducer resistance, the directivity index (DI) and the wave impedance of the sound. For fresh water at 20°C

$$10 \log (\eta_x) = S_x - (71.5 + 10 \log R + DI)$$

$$-71.5 = 10 \log \left(\frac{4\pi d^2}{\rho c}\right) - 20 \text{ dB}$$

$$\rho c = 1.48 \times 10^6 (\text{SI}) \text{ for fresh water } 20°\text{C}$$

$$d = .91\text{m or } 1 \text{ yd}$$

The directivity index is determined from charts, sonar transducer slide rules or integration of the vertical directivity pattern. In general the -6 dB beamwidth and a check of the minor lobe levels to see if they are close to the theoretical values for a uniform line are sufficient information for determining the directivity index. The first minor lobe should be -13 ± 1/2 dB re the main beam level.

No measurement is required of test distance between the measured transducer and the near-field calibration array. The measured transducer must, however, be within the constant plane wave region of the NFCA acting as a source. This is true for either transmitting and receiving with the measured transducer. Orientation, the direction of plane-wave propagation, must be determined accurately for reference of the azimuth position of the hydrophone to the flux gate compass.

All acoustic measurements are obtained with pulsed sound under conditions that established the transducer characteristics (source level, response, sensitivity, directivity, stiffness ratio and impedance) under continuous wave, steady state conditions. Figure 6 and 7 show,in block diagram form,the electronic calibration circuit required to obtain these data. The signal source produces a nominal 1 volt into 75 ohms with distortion, harmonic and spurious, more than 60 dB down. The transmit signal gate normally triggers on the axis crossing with isolation and switching transients more than 60 dB down. The pulse timing generator produces a 10 volt signal for synchronizing the transmit signal with the measurement of impedance and a delayed receiving gate for measurement of amplitude and phase of the hydrophone output voltage. Specified ranges are 1 to 3 msec transmit pulse duration, 1 to 10 pulses per second, 0 to 1 msec delay to receiving gate, .5 to 3 msec receive gate duration.

The E-I normalizer is a servo controlled attenuator that maintains a preset voltage or current drive to the transducer. For this system in which the measurements are made at only three frequencies the E-I normalizer is optional equipment. Some means of measuring voltage and current is required.

A nominal 10 watt amplifier is shown for driving the nearfield calibration array of approximately 50 ohms reactive impedance with 30 ma. The amplifier signal distortion with this load should be less than 1%.

The acoustic receiving circuit is shown in block diagram Fig. 7. It consists of a beam switching network for selecting the desired beam for measurement of the hydrophone array, preamplifiers, a band pass filter, attenuator and digital display of r.m.s. received voltage and phase referred to the signal source in Fig. 6. The received voltage will range between one millivolt and one volt. The signal source is connected through a calibrator that establishes a true r.m.s. reference voltage ± 1%. Rotator position is shown on the synchro display.

This can be a digital display with an accuracy of 0.01° but 0.1° accuracy is sufficient for this system. Digital r.m.s. voltage can be obtained with accuracy to 0.25 dB in the frequency range of 10 kHz. Phase measure is generally to an accuracy of ± 1° for pulsed sound measurements. It is possible to achieve greater accuracy in the measurement of phase by computer processing. A digital storage oscilloscope with magnetic tape storage could measure up to 200 samples per cycle at 10 kHz. With a 12 bit analyzer the ultimate phase resolution would be 0.1°. The Nicolet Model 1090 Digital Storage Oscilloscope produced by Nicolet Instrument Copr. is an example of this type of instrumentation.

CONCLUSIONS

A nearfield sonar test facility has been described that will conveniently and economically provide the Naval Air Rework Facility with full power measurements of the sonar source and low signal calibration of the sonar hydrophone. Minimum requirements can be met with a single, bridge-mounted rotator and digital readout of voltage, impedance, azimuth position and phase. A polar pattern recorder (not shown) would be helpful in the periodic check of data accuracy and the measurement of receiving, azimuth sum-beam intersections. As the work load increases the installation of a submerged rotator would reduce the hydrophone array calibration time from 4 hours to 2 hours.

Deaeration of the water will permit full power measurement of the sonar projector at the shallow calibration depths that facilitate transducer handling. Air bag support of the tank will insure maximum transmission loss for ground conducted noise from engine test facilities, ground transportation and airport traffic. Acoustic treatment of the room will be required to maintain a low ambient noise in the water. NRL has found that cooling fans in the electronic measuring system produce a 4 to 6 dB increase in the level of underwater ambient noise. The electronic system for this proposed facility should be housed in a separate room. The water circulating pumps for filtering and deaerating must be shut off during hydrophone measurements. At NRL these pumps raise the spectral noise pressure at 10 kHz by 15 to 20 dB.

Procurement will probably require more than one contract due to the multiplicity of technical areas. Four nearfield calibration arrays have been built by NRL. The proposed array can be built by the Underwater Sound Reference Division of NRL. The wood stave tank is a commercial product available from a number of manufacturers. The deaeration equipment is used in the chemical and petroleum industry for inhibiting corrosion and bacterial growth in cooling water systems. The electronic measuring system is an assembly of standard products from a number of sources and can be packaged by a systems engineering company.

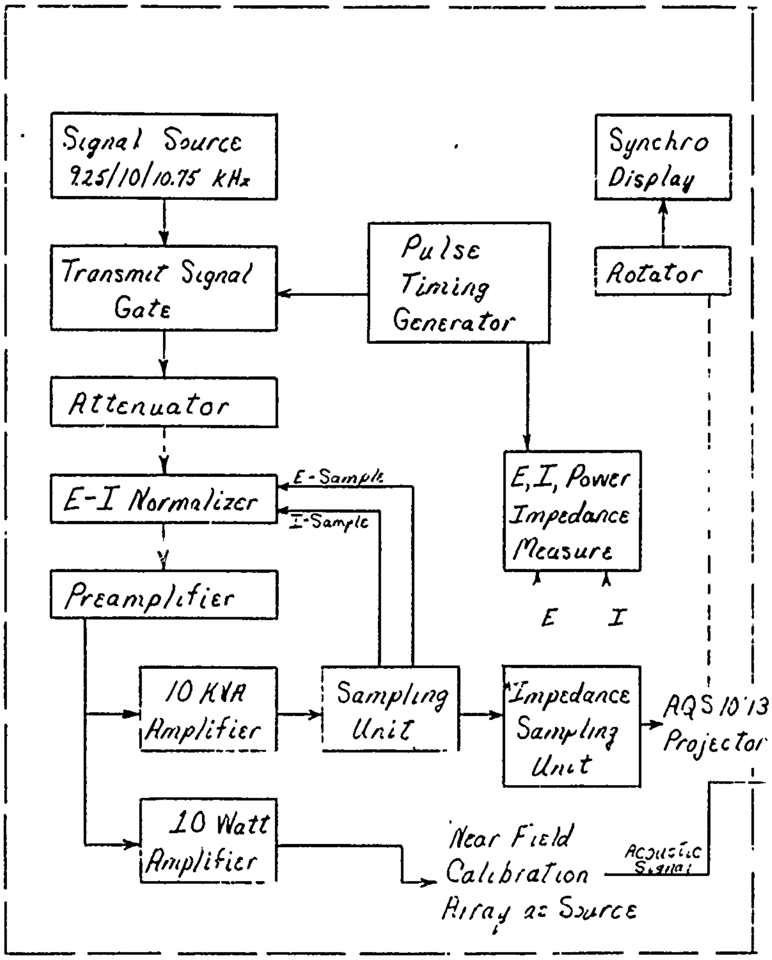


Fig. 6 — Block diagram acoustic source

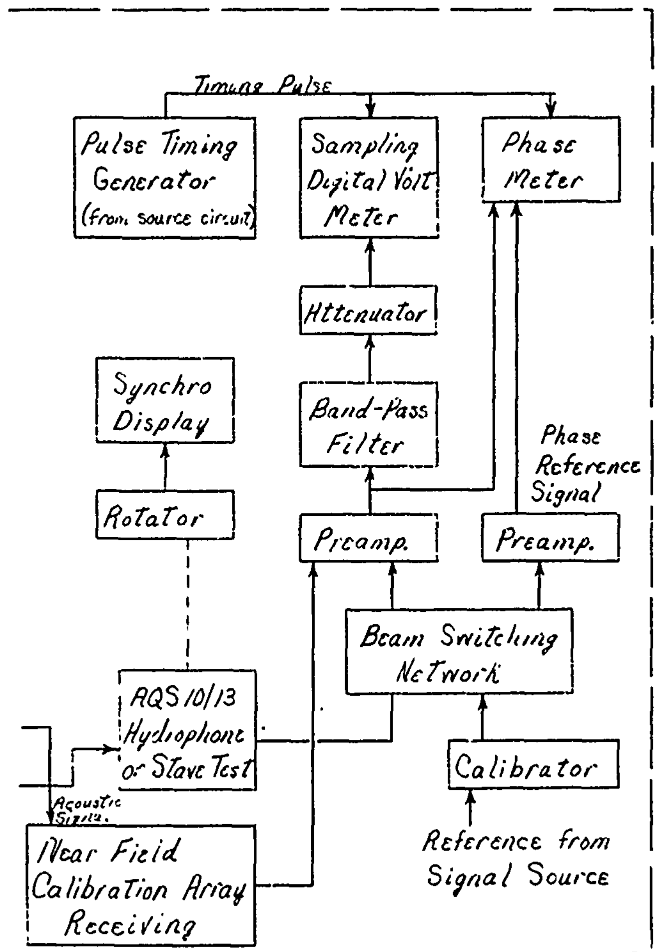


Fig. 7 — Block diagram acoustic receiving circuit

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